

#### **Einstein**

Energy can be converted to mass Kinetic energy can create particles

#### Dirac, Anderson

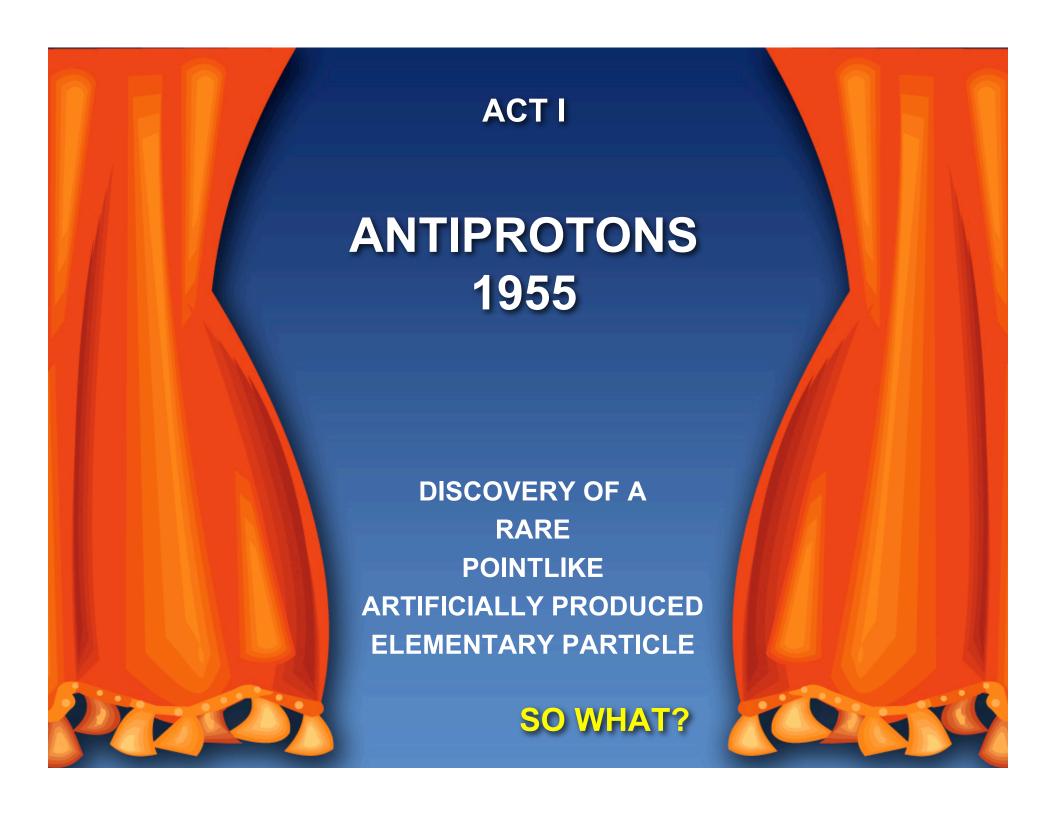
Theoretical prediction and experimental discovery of e<sup>+</sup>

#### Pauli, Majorana, Reines - Cowan

Theoretical prediction and experimental discovery of a fermion which can mix with its antiparticle.

#### **Big Bang theory**

# **ACCELERATOR DEVELOPMENT !!!**



# Chamberlain, Segre, Wiegand, Ypsilantis:



First particle discovered in an accelerator

Soon after -

Cork, Piccione, Wenzel, Lambertson:



Later: anti-nuclei, anti-atoms (even anti-virus...)

**ANTIMATTER IS HERE!** 

## p, hence $\overline{p}$ , is not pointlike

- $\overline{p}p \rightarrow e^+e^-$  Not given by QED
- $\overline{p}p \rightarrow n \pi$  High multiplicity

### **p** beams

## pp annihilations

- Discovery of  $\omega$ -meson in  $\overline{p}p \rightarrow 5\pi$
- Victory of flavor SU(3)

$$\overline{p}p \rightarrow \pi^+\pi^-, K^+K^-, K^0 \overline{K}^0$$

# Years later: pp colliders

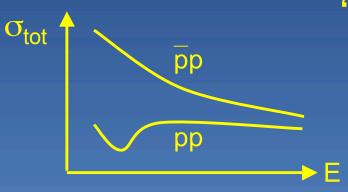
- W, Z
- t quark

# pp annihilations

$$\overline{p}p \rightarrow \pi\pi$$
,  $\pi\pi\pi$ ,  $K\overline{K}$ ,  $K\overline{K}\pi$ , ...

**High Multiplicity** 

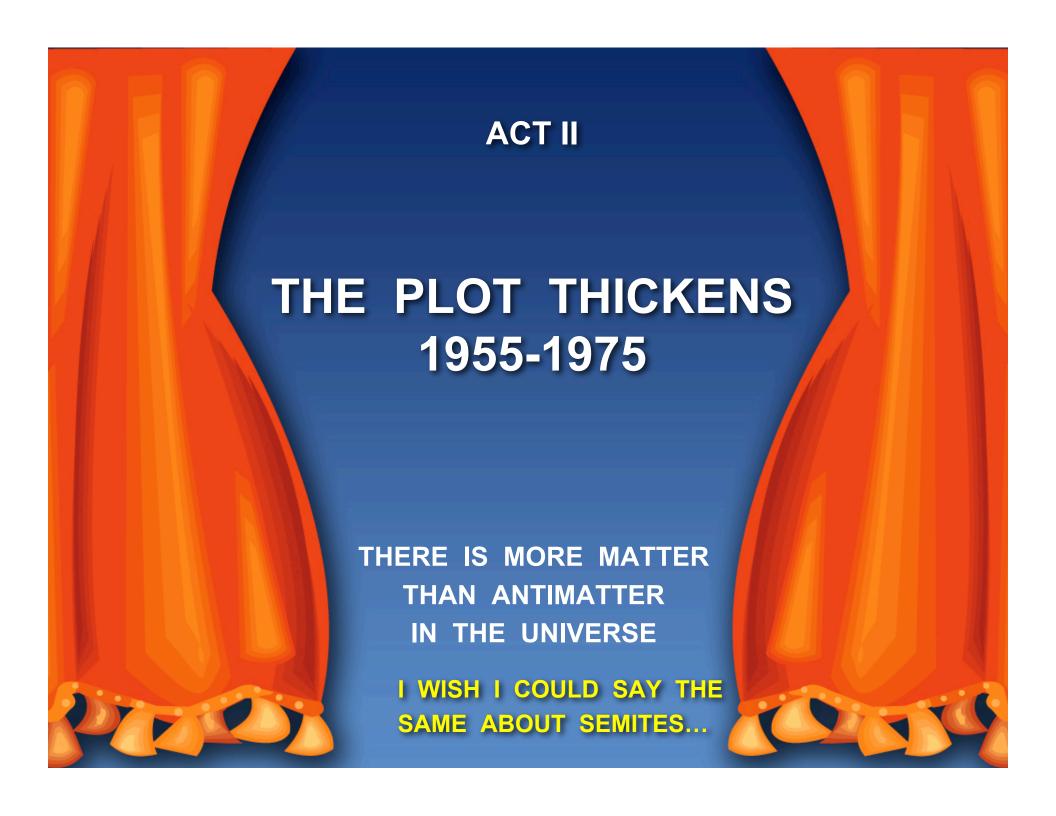
$$\sigma_{\text{tot}}(\overline{p}p) > \sigma_{\text{tot}}(pp)$$



"Anything you can do,
I can do better"

Is 
$$\sigma_{tot}$$
 (pp) -  $\sigma_{tot}$  (pp) =  $\sigma$  (pp  $\rightarrow$  mesons)?

No!!!



### **Big Bang Theory and Experimental Evidence**

Penzias - Wilson, Dicke, many others

At Big Bang: Equal numbers of protons and antiprotons

### **C-Violation and CP-Violation**

Lee-Yang, Wu

**Cronin-Fitch** 

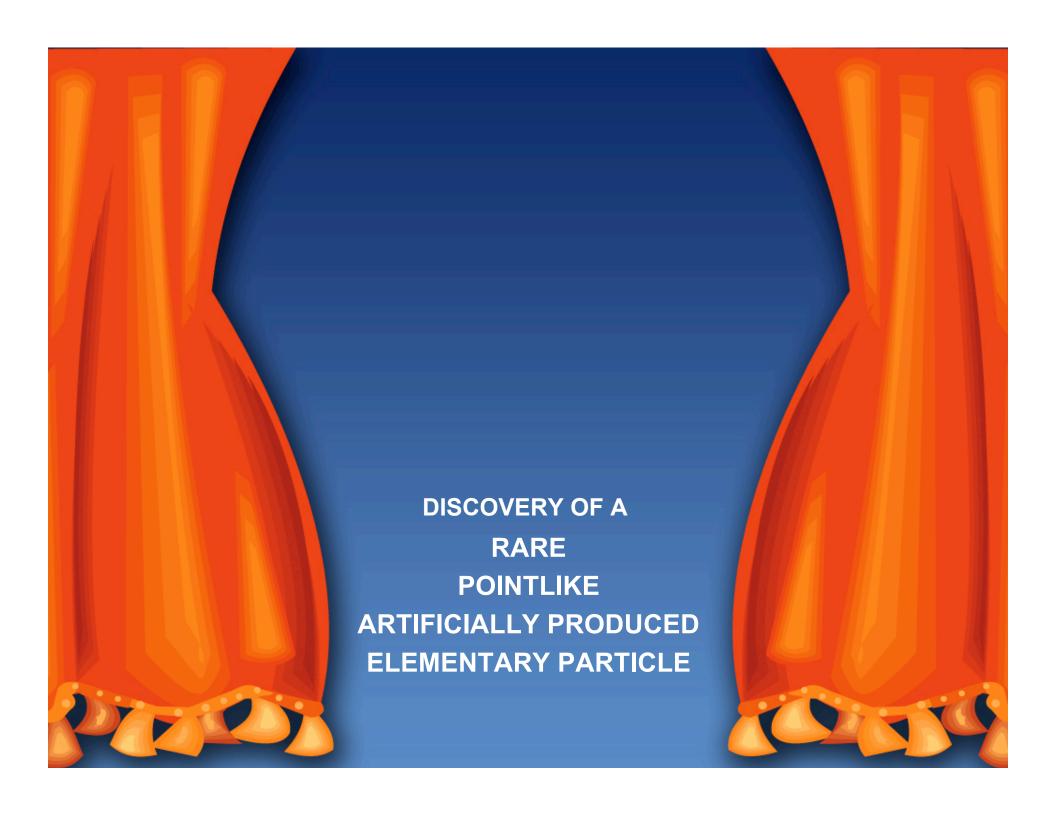
Antiprotons and protons can do different things:

$$\sigma(A \to B) \neq \sigma(B \to A); \quad \sigma(A \to B) \neq \sigma(\overline{A} \to \overline{B})$$

#### Quarks

Gell-Mann - Zweig

Protons and antiprotons are composite



Antiproton is not rare at all. In early universe: almost as frequent as protons

$$\frac{n (B) - n (\overline{B})}{n (B)} \sim 0(10^{-9})$$

Rich internal structure:
Form factors; Anomalous magnetic moment

The problem is not to produce them.

The problem is how they disappear and we survive.

**ARTIFICIALLY PRODUCED** 

**ELEMENTARY PARTICLE** 

Made of quarks

### Why are we here?

Sakharov-1967

- B-Violation
- CP-Violation
- Non-equilibrium

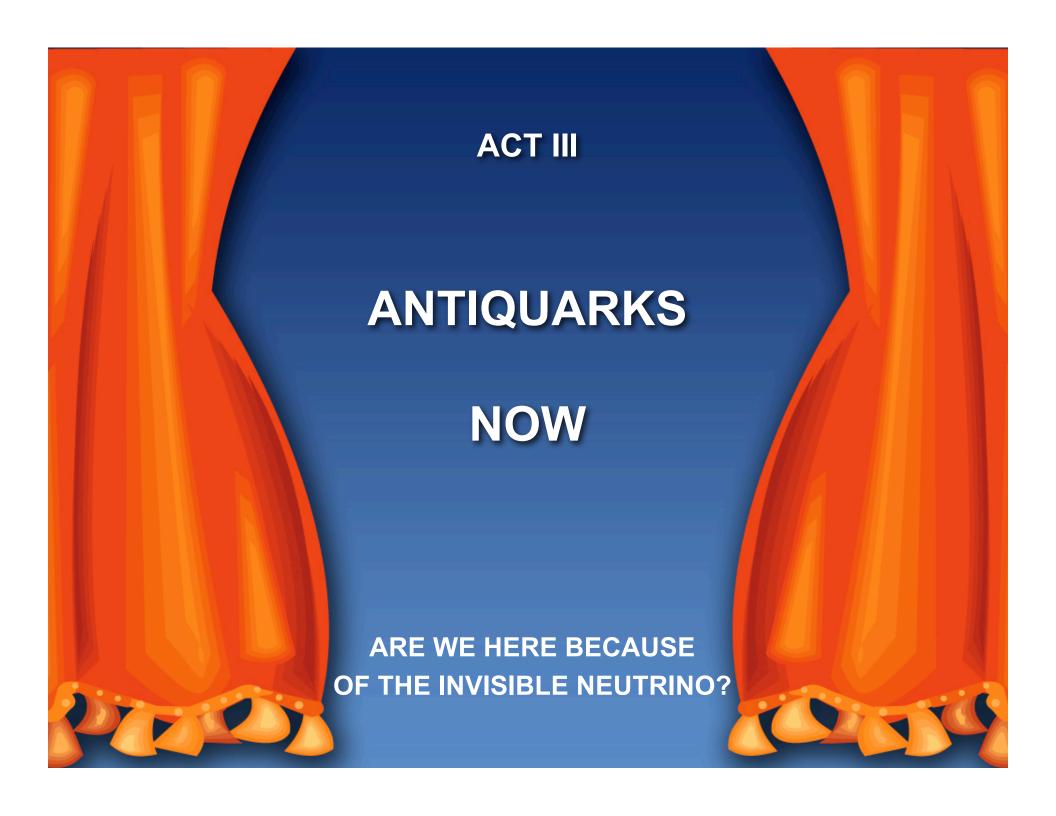
### **B-Violation (and L-Violation?)**

p-decay
GUT scale or higher
Not seen (but SN87A!)
v-oscillations and mass

### **CP-Violation**

KM phase for quarks (requires 3 generations) CP-violation in leptons (requires 2 generations)

## WHEN AND HOW DID IT HAPPEN?



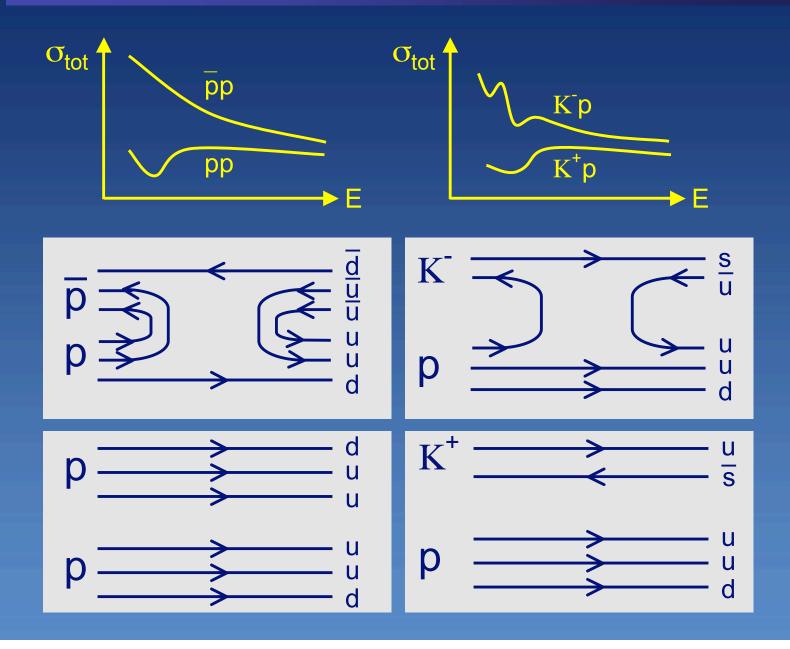
Both contain quarks and antiquarks and so do mesons.

Both pp and  $\overline{p}p$  collisions have qq,  $q\overline{q}$  and  $\overline{q}\overline{q}$  collisions!

It is just a matter of

**ENERGY, INTENSITY, BACKGROUND and ECONOMICS.** 

# What matters is qq annihilations!



# Why are we here?

At Big Bang: B=0, L=0 (also B-L=0)
We need to create a nonzero B (also B-L?)

"Leptogenesis" (other theories: GUT, electroweak):

If we could create a nonzero L
and then trade B for L,
we could create a positive B.

IT IS NOT ENOUGH TO TRADE B for L
WE MUST ALSO CREATE B-L

## B and L violation in the standard model (but no B-L)

"instanton" terms:  $(q_iq_jq_k)(q_iq_jq_k)(q_iq_jq_k)(\ell_i\ell_j\ell_k)$ i,j,k = generations

**"SPHALERON":** Connecting degenerate ground states

L and B can change (together) each by 3 UNITS (for  $N_g = 3$ )

B - L is conserved (and must be nonzero)

B + L is violated (and can trade B for L)

e.g.  $\Delta(B + L) = 6$  is allowed

## THE STANDARD MODEL CREATES (together) B AND L

#### The universe is made of

### **QUARKS** and **LEPTONS**

Neutrino oscillations  $\Rightarrow m(v) \neq 0$ , very small

Seesaw mechanism: 
$$\begin{pmatrix} 0 & m \\ m & M \end{pmatrix} \Rightarrow m(v) \sim \frac{m^2}{M}$$

Hence: v is a Majorana neutrino  $\langle vv \rangle \neq 0$ ,  $\bar{v}$ -v mixing, heavy neutrino with mass M

L=0 AT BIG BANG BUT △L ≠ 0 PROCESSES ARE ABUNDANT!

#### **LEPTOGENESIS**

At Big Bang: B = L = 0.

Majorana:  $\Delta L \neq 0$  and  $\Delta (B-L) \neq 0$  are allowed.

Hence, the universe has  $L\neq 0$  and  $B-L\neq 0$ .

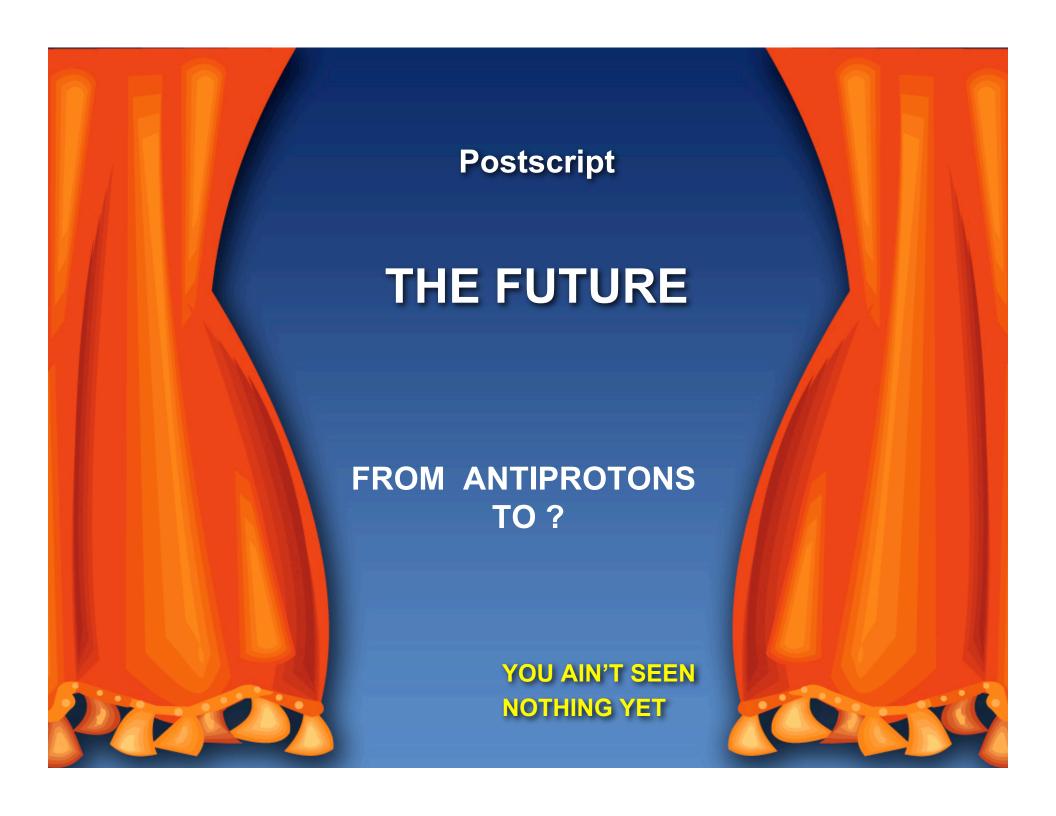
**LEADING TO B≠0 !!!** 

(Elaborate quantitative estimates).

e.g. Buchmueller-Peccei-Yanagida

The particle, which is its own antiparticle, is responsible for having more particles than antiparticles in the universe

NECOGINO ERGO SUM



If all building blocks were charged, we would have equal amounts of matter and antimatter.

The universe has equal number of positive and negative charges.

We exist thanks to neutral particles, transforming into their own antiparticles.

Perhaps it all happens at the subparticle level !?

No evidence for subquarks and subleptons.

No reasonable dynamical theory

Why q and 
have simple charge ratios?

$$(+^2/_3, -^1/_3)$$
 (0, -1)

- Why p and e<sup>+</sup> have same charge?
- Why ΣQ<sub>i</sub> = 0 for q'<sub>s</sub> and ℓ'<sub>s</sub> in one generation?

$$[\Sigma Q_i = (-1) + (0) + 3(+2/3) + 3(-1/3) = 0]$$

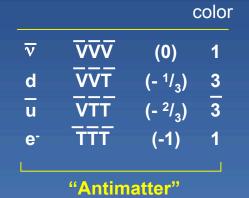
Why three colors and three generations?

PREONS? TOY MODELS?

### **Rishons**

	Q	SU(3) <sub>H</sub>	SU(3) <sub>c</sub>	N <sub>T</sub>	N <sub>V</sub>	3(B-L)
Т	+ 1/3	3	3	1	0	1
V	0	3	3	0	1	-1
V	0	3	3	0	-1	1
T	- <sup>1</sup> / <sub>3</sub>	3	3	-1	0	-1

			COIOL	
e⁺ u d v	TTT TTV TVV VVV	(+1) (+2/ <sub>3</sub> ) (+1/ <sub>3</sub> ) (0)	1 3 3 1	SU(3) <sub>H</sub> Singlets
	"Ma			



e<sup>+</sup> TTT

p TTT(TT)(VV)(VV)

e TTT

TTT(TT)(VV)(VV)

Anomaly cancellation:  $N_H = N_C = N_G = 3$ 

### **Rishons**

	Q	SU(3) <sub>H</sub>	SU(3) <sub>c</sub>	N <sub>T</sub>	N <sub>V</sub>	3(B-L)
Т	+ 1/3	3	3	1	0	1
V	0	3	3	0	1	-1
V	0	3	3	0	-1	1
T	- <sup>1</sup> / <sub>3</sub>	3	3	-1	0	-1

color						color			
e <sup>+</sup> u d	TTT TTV TVV VVV	(+1) (+2/ <sub>3</sub> ) (+1/ <sub>3</sub> ) (0)	1 3 3 1	SU(3) <sub>H</sub> Singlets	⊽ d u e	VVV VVT VTT TTT	(0) (- <sup>1</sup> / <sub>3</sub> ) (- <sup>2</sup> / <sub>3</sub> ) (-1)	1 3 3 1	
"Matter"						"Antim	atter"		

TO BREAK B-L WE NEED TO BREAK N<sub>V</sub>

Simplest J=0, Q=0,  $SU(3)_H$  – singlet,  $SU(3)_C$  – singlet

IS <VVVVV>: BREAKS L, HENCE CREATES B

<VVVVV>≠0 ERGO SUM

